21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

2016 CIGRE-IEC Colloquium
May 9-11, 2016
Montréal, QC, Canada

DC transformer bushing replacement program in MH HVDC converter stations – implementation of RIP silicone rubber bushing design

R.BRAY — Manitoba Hydro, Canada
B. SCHLITTLER, C.KRAUSE — Weidmann ET AG, Switzerland
D.JAHNEL — HSP, Germany
W.ZIOMEK — PTI Manitoba Inc., Canada

SUMMARY

Since 1970's Manitoba Hydro (MH) operates The Nelson River HVDC transmission lines accommodating two bipolar links: Bipole I (450 kV_{DC}) and Bipole II (500 kV_{DC}). The transformers' reliability is safeguarded through maintaining the fleet of spare units; however the risk of operating these units with some 40 year old DC bushings was a reason for serious concern, as these bushings with their insulation are most stressed components in the transformers. During the evaluation of the available bushing information, it was discovered that there was no useable design information for the bushings and insulation structure. In 2011, due to change of ownership of the bushing supplier and unavailability of special low-resistivity porcelain, the OIP bushings for DC applications were no longer offered and RIP bushings became the only obtainable option. MH realized that the relatively new second generation transformers would be left without replacement OIP bushing, exposing the 26 converter transformers to an increased risk and reduced asset life. The DC RIP bushing replacement program for 300, 450 and 500 kV_{DC} operating voltage was therefore prepared which subsequently had to overcome numerous problems: (i) the units were built by different manufacturers, hence their active participation was required, (ii) the old type bushings were no longer available and new bushings needed to be mechanically and electrically fitted in the old units, i.e. the electric stress distribution of new bushings had to meet design limits. Moreover, the bushing corona shield electrodes had to fit in the pressboard barrier systems of different transformer suppliers. In addition, the new bushing development was to be incorporated into all future transformers so that there was only one bushing design for each DC voltage class. The paper describes the design aspects of the DC bushing replacement, including differences in dielectric performance of different insulation materials and insulating systems employed in this program, as well as logistics of the replacement program. The bushing supplier and insulation supplier worked with three transformer manufacturers to ensure that the newly developed RIP bushings will work with old and new transformer insulation systems and meet new MH specification requirements. First 500kVdc voltage class bushings were already successfully tested at the bushing manufacturer factory and are awaiting installation in the field.

KEYWORDS
HVDC converter transformer, DC bushing, DC bushing insulation, asset management

wziomek@partnertechnologies.net

1. INTRODUCTION

The asset management for large HVDC systems is a complicated task which often requires making difficult choices between maintenance, replacement and/or expansion of assets.

Since 1970's Manitoba Hydro (MH) operates The Nelson River HVDC transmission lines accommodating two bipolar links: Bipole I (450 kV_{DC}) with northern terminus at Radisson Converter Station near Gillam and Bipole II (500 kV_{DC}) which extends northeast to Henday Converter Station. The southern terminus of both 900-km long DC transmission lines is Dorsey Converter Station at Rosser, near Winnipeg [1].

In 2009, MH started an initiative to assess the risks associated with its aging transmission system infrastructure and to establish long term plans and budgets to manage these risks. Three most critical assets were identified: transformers, circuit breakers and transmission lines.

The transformers' reliability is safeguarded through maintaining the fleet of spare units. However the risk of operating these units with some 40 year old DC bushings was a reason for serious concern, as these bushings with their insulation are most stressed components in the transformers. During the evaluation of the available bushing information, it was discovered that there was no useable design information for the bushings and insulation structure. In 2011, due to change of ownership of the bushing supplier and unavailability of special low-resistivity porcelain, the OIP bushings for DC applications were no longer offered and RIP bushings became the only obtainable option. It became apparent that MH had to start gathering all critical data from the OEMs for the transformers which were replaced since 1997 and which were all equipped with OIP bushings from Trench UK. MH realized that the relatively new second generation transformers would be without replacement OIP bushing, exposing the 26 transformers to an increased risk and reduced asset life. Therefore, the DC RIP bushing replacement program for 300, 450 and 500 kV_{DC} operating voltage was therefore prepared with HSP, Germany. This program subsequently had to overcome numerous problems: (i) the converter transformers were built by different manufacturers, hence their active participation in the replacement project was required, (ii) as the old type bushings were no longer available, the new, specially developed RIP bushings needed to be mechanically and electrically fitted in the old units, i.e. the electric stress distribution of new bushings had to meet design limits. Therefore, the requirements of the bushing compatibility program included the future replacement of the OIP-bushings with porcelain sheds by the RIP-bushings with silicone rubber sheds which had the electric field distribution with appropriate safety margins and their bushing corona shield electrodes had to fit in pressboard barrier systems of different transformer suppliers. In addition, the new bushing development was to be incorporated into all future transformers so that there was only one bushing design for each DC voltage class.

According to the industry standards [2,3] the DC bushings require a factory testing with their own insulation system (i.e. pressboard moulded barriers and a stress shield), therefore the newly developed DC bushings with silicone sheds needed to be tested with their own insulation systems in the test tanks before installation in the transformers. In order to achieve successful prototype testing, the elaborated field studies of bushing insulation systems for the transformers and the test systems was performed, addressing the strike in oil (i.e. stress across the oil gaps), creep, and maximum local stress (point stress) in oil, pressboard and at the bushing surface under AC, DC and Polarity Reversal excitations. Moreover, the current densities in the leads, mechanical fitting of all components, assembly tolerances, etc., had to be addressed.

The paper describes the design aspects of the DC bushing replacement, including differences in dielectric performance of different insulation materials and insulating systems employed in this program.

First 500 kV_{DC} voltage class bushings were already successfully tested at the bushing manufacturer factory and are awaiting installation in the field.

2. DC BUHINGS – GENERAL COMMENTS

Two types of DC bushings are used: (i) conventional, with porcelain sheds, oil filled, with oil impregnated paper insulation (OIP) between aluminium foils, or (ii) composite, dry-type, with silicone rubber sheds and resin impregnated paper (RIP) internal insulation.

Conventional DC bushings were built using special, low sodium, low resistivity porcelain with resistivity of ~10^{10} Ωm compared to ~10^{12}-10^{14} Ωm for standard, AC-type application porcelain. As this kind of porcelain is no longer available in the market, the modern design is based on silicone rubber insulation.
Compared to porcelain, composite bushings provide better protection against dust and debris.

The requirements of modern DC bushings are following: (i) fulfilment of all requirements of IEC 62199 or IEC/IEEE 65700.19.03, (ii) no oil filling on the valve hall side and (iii) extreme high creepage distances on the air side, in particular for open-air-bushings.
In a modern design the current-carrying conductor is placed in a resin impregnated condenser bushing core, enclosed with a glass fiber impregnated epoxy tube. This tube is filled with a foamed elastomer which forms a solid, flexible connection between the elements, or with SF_6 under a few bar pressure. The silicone sheds and the flanges are directly vulcanized onto a fibre-glass reinforced epoxy tube. The length of such a bushing can be in the range ~10 m. The creepage length can be in the order of 24 m.

In the past the DC bushings faced many problems, but the present day bushings are nearly as reliable as AC bushings. It results from application of new materials but also from better understanding of the specifics of HVDC insulation. The dry type bushings (RIP) are becoming a dominating option throughout the HVDC industry.
Winding lead exits and the location of the Valve (DC) bushings depends on the type of transformer and its position to the valve hall. The DC bushings are sensitive to pollution. The horizontally mounted DC bushings are inserted directly into a valve hall and this reduces the pollution problems. It needs to be emphasized that the test levels for bushings are 15% above the dielectric test levels for transformers. The design of the interface between the DC lead insulation and the bottom end of the bushings has to be closely coordinated between the transformer, insulation and bushing manufacturers. The AC, DC and Polarity Reversal (PR) field distribution and voltage stresses have to be examined in detail, before the dielectric test [4-7].

Electrical requirements include: (i) voltage withstand tests, (ii) partial discharge test, (iii) dissipation factor and capacitance measurements, and (iv) creepage distance.

Mechanical requirements for DC bushings include: (i) dimensions and tolerances, (ii) cantilever strength, (iii) internal pressure and vacuum level, and (iv) the draw lead bushing cap pressure. Moreover, apparatus bushings shall be designed to withstand full vacuum when mounted in the apparatus tank.

3. PROTOTYPE REQUIREMENTS, THE DC BUSHING TEST TANK

Most of the dielectric routine and type tests can be carried out with the bushing axis at any inclination, regardless of its intended service angle where appropriate. The wet switching impulse voltage withstand test and the thermal, mechanical and special tests shall be carried out with the bushing mounted at its intended service angle, unless other arrangements have been agreed and if shown compatible and sufficient.
DC tests on the converter transformer and reactor bushings shall be carried out with external insulation (barriers) and ground planes surrounding the lower end of the bushing in a position as similar as possible to that of the intended service condition. The simulation of the insulation arrangement may be agreed between the manufacturer and the purchaser.
In cases where a bushing is exposed to DC applied voltage withstand and Polarity Reversal tests and it is tested with a temporary insulating barrier system in oil, it is recommended that the conductivity and fibre content of the oil are recorded.
DC tests on wall (roof) bushings shall be carried out with wall ground plane and mounting arrangements as similar as possible to that of the intended service condition.

Except for mechanical tests, all tests shall be carried out with the bushing mounted on a supporting structure with its ends in the media of the type in which they are intended to operate.
As clearly indicated in the standards, the dielectric tests – especially DC and PR tests – need to be performed in the test vessel (see Figure 1) with complete insulation system similar to one used in the transformer. This is required, as the geometry and material characteristics of bushing insulation and moulded pressboard insulation will have influence on the DC field distribution and resulting DC stresses at the surface and inside the bushing.

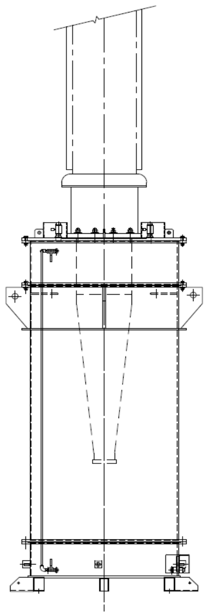

Figure 1 Example of a test tank – for 500kV DC bushing testing (moulded pressboard insulating system not shown)

4. FIELD PLOTS — EXAMPLE FOR 500KV DC BUSHING TEST SYSTEM

4.1. General steps

The insulation supplier models the geometry of the bushing with corona shield and pressboard insulation inside the test tank. This can be done in a 2D electric field program with rotational geometry. The test voltages are applied. Then the most stressed areas are analyzed for the point stress, strike in oil (under ac) and creep stress (ac, DC and PR). The actual stresses are compared to the design limits. In case of high stresses developing in the system, the designer may increase the amount of insulation, increase the gap between HV and grounded parts, change the geometry of the components, until the required safety margin is achieved. Depending on who is responsible for a specific component – this partner will need to change the properties and be responsible for its final performance. In the following sections a 500 kV_{DC} bushing insulating system will be shown under AC, DC and PR fields.

4.2. AC field

The AC fields are well known, the calculations are routinely performed for all conventional transformers. The AC field distribution is driven by the geometry and permittivity of all components, as well as the potential at the electrodes. The example of the field distribution is shown in a Figure 2 below.

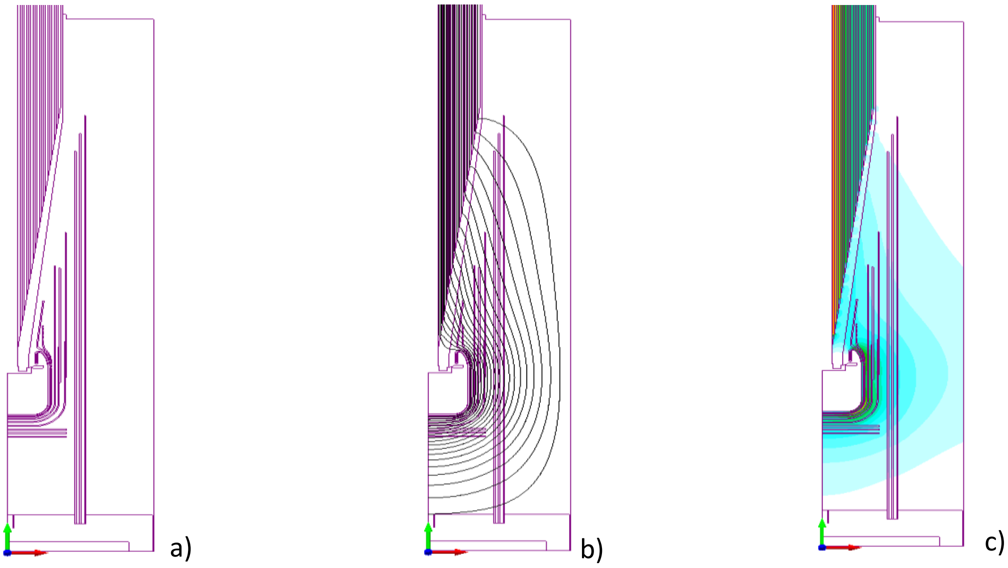

Figure 2 The AC field modeling of the 500kV DC bushing test system under 850 kV$_{RMS}$: a) geometry, b) equipotential lines, c) electric field distribution

4.3. DC field

The DC field distribution is driven by the geometry and resistivity of all components, as well as the voltage at the electrodes. The oil — with resistivity being one-two orders of magnitude lower than that of solid insulation — is barely stressed; the electric field is concentrated in the solid insulation. The example of the DC field distribution (the geometry with test voltage, equipotential lines and field intensity) is given in Figure 3 below.

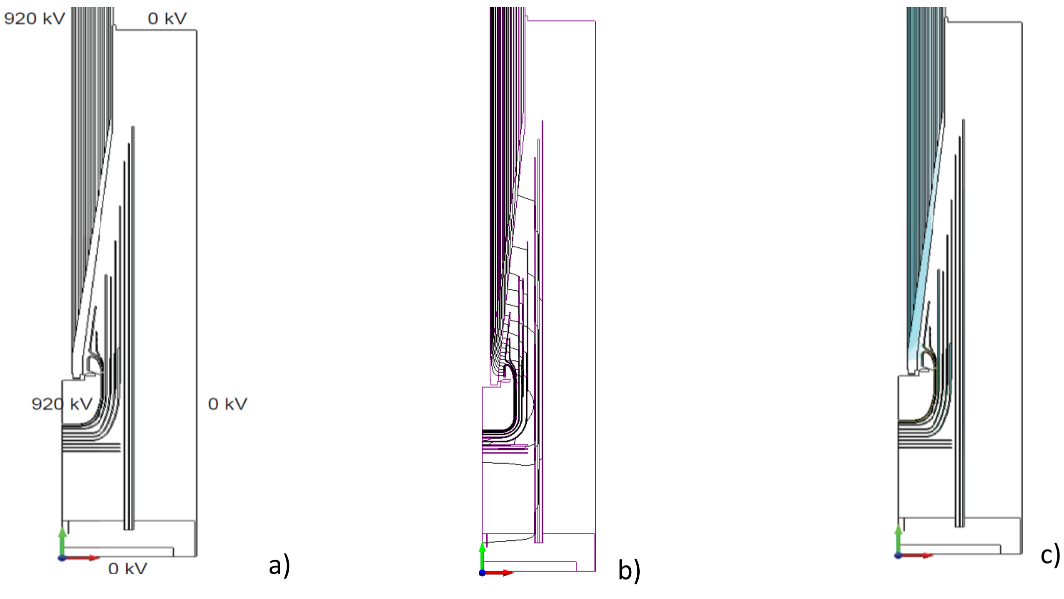

Figure 3 The DC field modeling of the 500kV DC bushing test system under 920 kV$_{DC}$: a) geometry, b) equipotential lines, c) electric field distribution

4.4. PR field

The high values of time constants (counted in hours) of oil/board insulation systems allow for a calculation of the electric field immediately after the polarity reversal by superimposing the existing

DC field distribution and an AC field distribution of twice the magnitude and opposite polarity (i.e. DC – 2 ·AC); this method is used in the example below.

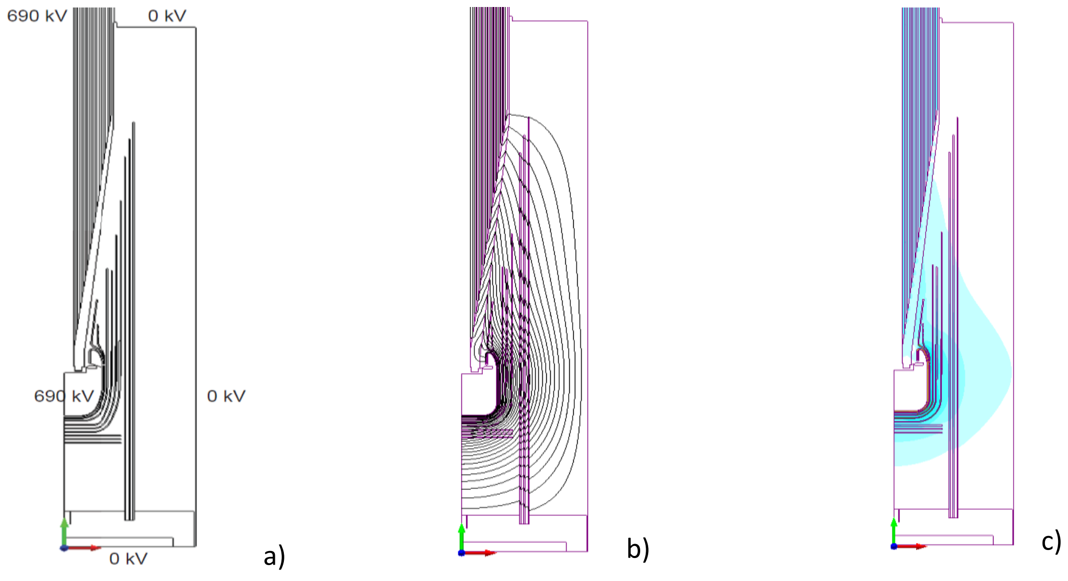

Figure 4 The PR field modeling of the 500kV DC bushing test system using DC-2·AC method under 690 kV: a) geometry, b) equipotential lines, c) electric field distribution

The modern field programs allow for time-dependent studies of field stresses (see Figure 5) – this study was performed as well, to verify the results of the DC-2·AC simulation.

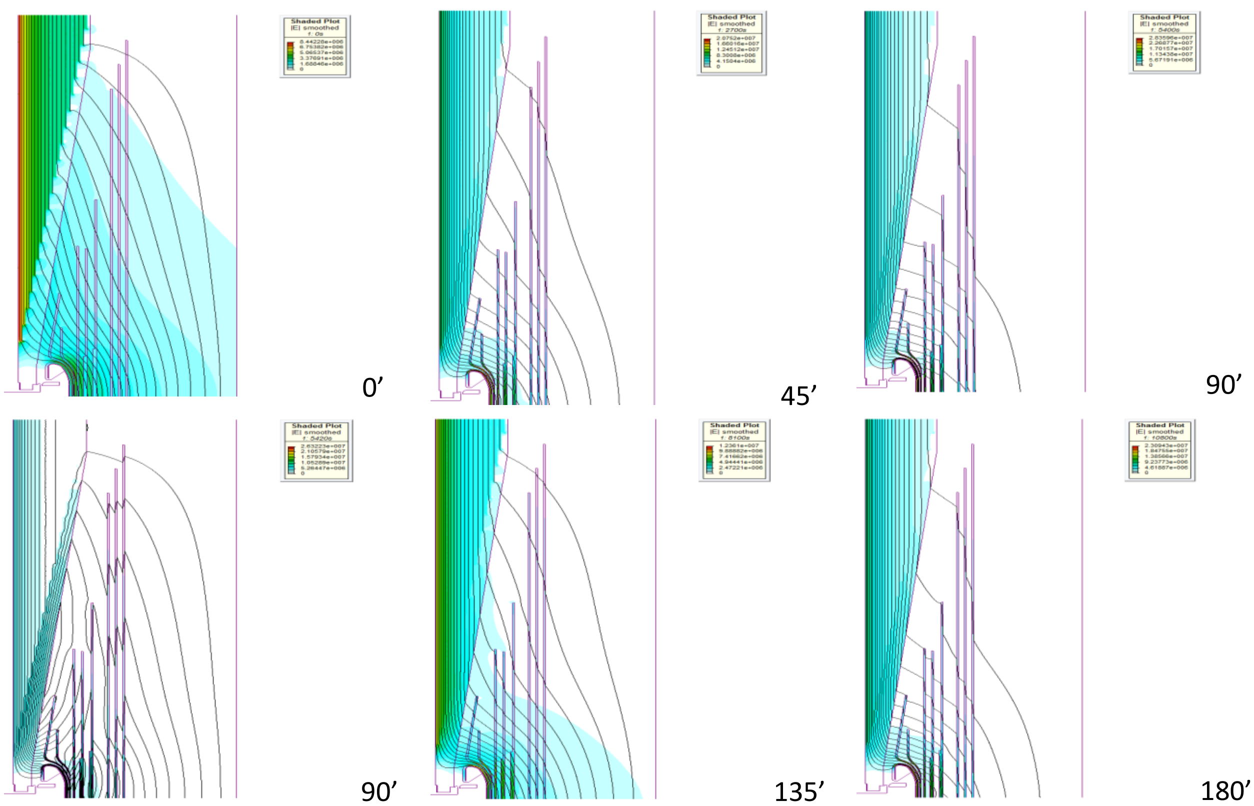

Figure 5 The electric field distributions during polarity reversal test as a function of time [minutes]: -690kV for first 90 minutes, +690 kV for next 90 minutes (remaining final 45 minutes at -690 kV not shown);

The time resolved field studies allow for in-depth analysis of the electric stresses in all areas. The analysis is automated, with corresponding animations. The transient study results shown in Figure 5 allow to follow the changes in the field distributions: (i) just after the application of -690 kV at time 0, the distribution is capacitive, slowly changing into resistive type - see the field plots at 45 minutes and 90 minutes, (ii) at the application of +690 kV in 90^{th} minute the distribution abruptly changes from resistive to capacitive and then continues to change into the resistive type – see the field plots at 135 and 180 minutes.

The field stresses were checked during the course of the PR test simulations in time domain and mostly conformed to the results obtained using a conventional method. Only in a few locations the transient stresses were higher than those rendered with the DC-2·AC field simulation. These stresses were accepted, because the comparison of the momentary, transient field stresses against the criteria based on static distribution have significant safety margin.

4.5. Tolerances for field assembly

As during the field installation of the bushings with pressboard insulation the positioning of the new insulating system in the turret and also the position of the corona shield may be a few millimetres different from the ideal geometry, therefore some specific tolerances were assumed in radial and axial directions and all field plots were verified against such modified geometries.

4.6. Test voltages

The test voltages shown in Table I for the 500 kV_{DC} class bushings were used in the field simulations and later during the testing at the bushing manufacturer plant.

Table I Test voltages for AC, impulse and DC/PR tests with duration for 500 kV_{DC} bushing

	Duration	Voltage [kV]
AC 60 Hz	60 s	800
AC 60 Hz	60 min.	680
LI FW		1800
LI CW		2070
SI		1560
DC 2 h	120 min.	920
DC 2 min.	30 s ramp / 120 s steady voltage	1224
PR	90 min. neg./ 90 min. pos. / 45 min. neg.	690

5. CONCLUSIONS

The replacement of conventional OIP bushings with porcelain sheds by the specially developed, dry-type RIP bushings with silicone sheds was successful. All old OIP designs (300, 450 and 500 kV_{DC}) were replaced with new RIP bushings.

All technical problems, such as compatibility of the corona shields, assembly tolerances, and control of the electrical stresses were solved; with this development the new RIP bushings fulfilled all electrical and mechanical requirements.

First 500 kV_{DC} RIP bushing was successfully tested in the bushing manufacturer test laboratory.

BIBLIOGRAPHY

[1] R.Bray, M.Foata, M.Werner "Asset management strategy at Manitoba Hydro: Case example of the refurbishment of transformers at Dorsey substation", 2015 Cigré Canada Conference, Winnipeg, Manitoba, August 31-September 2, 2015

[2] IEC/IEEE 65700.19.03-2014 - IEC/IEEE International Standard - Bushings for DC application

[3] IEC 62199 ed1.0, "Bushings for d.c. applications", 2004 (withdrawn)

[4] K.C. Wen et al "A calculation method and some features of transient field under polarity reversal voltage in HVDC insulation", EEE Transactions on Power Delivery. Vol. 8, No. 1, January 1993

[5] F.Hammer, A.Küchler "Insulating Systems for HVDC Power Apparatus", IEEE Transactions on Electrical Insulation vol. 27 No. 3, June 1992

[6] A. Küchler, F. Hüllmandel, J. Hoppe, D. Jahnel, C. Krause, U. Piovan and N. Koch, "Impact of dielectric material responses on the performance of HVDC power transformer insulations", 8th Int'l. Sympos. High Voltage Eng., 2003

[7] Cigré Advisory Group B4.04 "HVDC LCC Converter Transformers - Converter Transformer Failure Survey Results From 2003 To 2012", Cigré Technical Brochure 617, 2015